FCC-ee Collider Magnet Field Correction

J. Bauche[1], C. Eriksson[1], F. Saeidi[2]
[1] *CERN, Geneva*
[2] *IPM, Tehran*

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Many thanks to all the members of the FCC collaboration.

Outline

Magnet specifications

Field quality with trim circuits
- Dipole
- Quadrupole
- Sextupole

Conclusions

Specifications

Magnet main specifications

- Includes **aperture reduction in SSS magnets**
- **Aperture in sextupole** assumes **no bake-out system** (as in CDR baseline)
- **Aperture in dipole** could **possibly be reduced** with vacuum chamber tapering's
- **Sextupoles** are present in only about **½ of the arc half-cells**
- **Field quality specifications** from latest beam dynamic studies

	Mag. Length [m]	Bore aperture (reduced) [mm]	Vacuum aperture (reduced) [mm]	Pole tip field [T]	Number of units (arcs)	Total magnetic length [km]	Ring filling factor (91 km) [%]
Dipole (S)	19.30	**42**	**35**	**0.061**	1128	21.77	
Dipole (M)	20.95				284	5.95	
Dipole (L)	22.65				1428	32.35	
Total					**2840**	**60.08**	**65.9**
Quadrupole	**2.9**	**37**	**30**	**0.438**	**2836**	**8.22**	**9.0**
Sextupole	**1.5**	**33**	**30**	**0.442**	**4672**	**7.01**	**7.7**

Arc magnet specifications from optics – May 2023 (K. Oide)

Error & maget type	Z	tt
b_3 in arc dipoles	2	2
b_3 in IR dipoles	0.1	0.5
b_3 in arc quadrupoles	10	8
b_3 in QY	0.1	8
b_3 in QC, QT, QA, QB, QG, QH, QL, QR, QU, QI	1	8
a_3 in QC1, QC2	1	5
b_4 in arc quadrupoles	10	10
b_4 in QC, QY	0.01-0.1	0.1
b_4 in QT, QA, QB, QG, QH, QL, QR, QU, QI	1	1
b_6 in arc quadrupoles	5	5
b_6 in IR quadrupoles	0.01	1

Magnet field quality specifications from optics – March 2023 (E. Ahmadi, R. Tomas)

Field tapering and correction circuits

Baseline

- **Field tapering** trims on each aperture of **dipoles** and **quadrupoles**
  → granularity: every 4 FODO
- **Orbit correction** and **skew quadrupoles**: trim coils in **sextupoles**
  → granularity: at every sextupole, so only at ~½ of the arc half-cells

➔ ***We studied options to remove orbit correction from sextupoles***

➔ ***Improve granularity*** *of correction*
➔ ***Free space*** *in the sextupole to* ***decrease*** *its* ***power consumption*** *(current density)*

BASELINE	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Sextupole	**1.5**	**0.013**	**0.02**
Orbit correction V	Sextupole	**1.5**	**0.013**	**0.02**
Skew quadrupole	Sextupole	**1.5**	**0.4**	**0.6**

Correction specifications from optics – April 2023 (K. Oide)

Alternatives

- **1) H + V orbit corrections** use **quadrupole tapering trim coils**
  → granularity: at every arc half-cell
- **2) H orbit correction** uses **dipole tapering trim coils +**
  V orbit correction uses **quadrupole tapering trim coils**
  → granularity: at every arc half-cell

ALTERNATIVE 1	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Quadrupole	**2.9**	**0.0067**	**0.02**
Orbit correction V	Quadrupole	**2.9**	**0.0067**	**0.02**
Skew quadrupole	Sextupole	**1.5**	**0.4**	**0.6**

ALTERNATIVE 2	Location	Mag. Length [m]	Peak field (B) or gradient (Q) [T] or [T/m]	Integrated strength [Tm] or [T]
Orbit correction H	Dipole	**21.15**	**0.0009**	**0.02**
Orbit correction V	Quadrupole	**2.9**	**0.0067**	**0.02**
Skew quadrupole	Sextupole	**1.5**	**0.4**	**0.6**

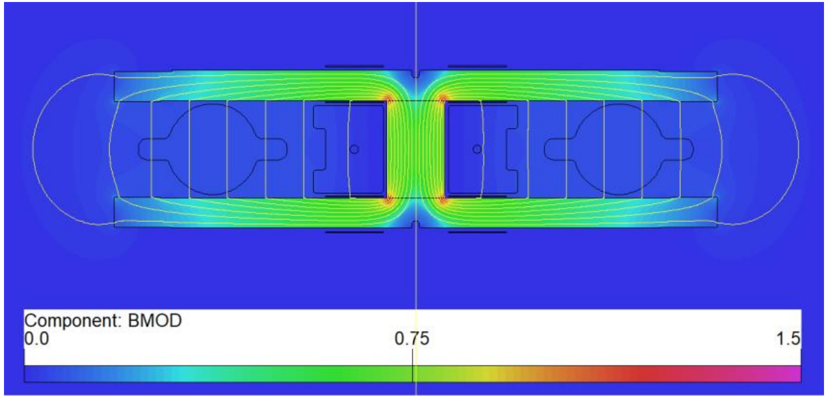
Dipole

Dipole design

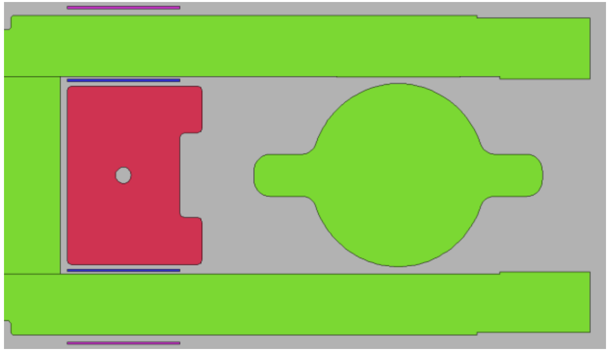
Trim coils

- Allow to modulate the field in the apertures independently
- Used for **field tapering** up to **±2.5 %** (tt_{bar})
- Used for **field tuning** up to **±1 %** (all phases)
  → **Granularity depends on number of circuits**
- If field tuning granularity matches orbit correction one, can be used for **H orbit correction** (up to **±1.5 %**)

→ **Worst case**: could be up to **5% of main field** variation



Magnetic model cross-section (tt_{bar} excitation, B = 61 mT)

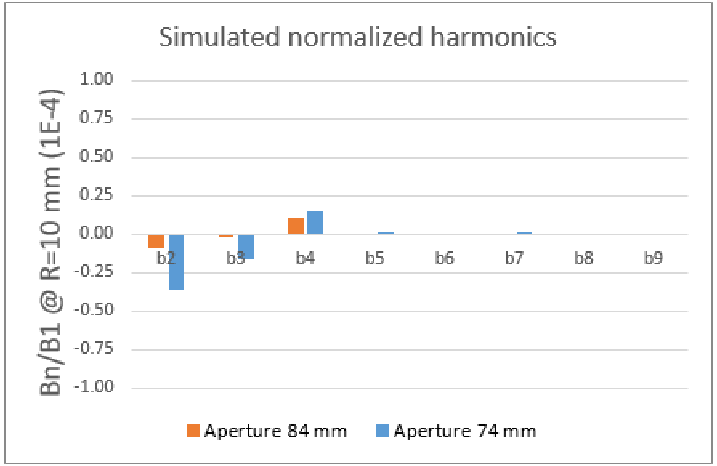


Trim coils wrapped around top and bottom poles

Dipole field quality

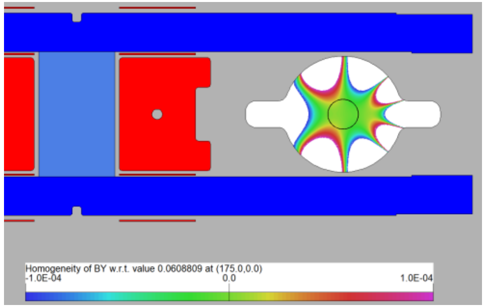
<u>Case 1</u>: peak current, trim coils off (182.5 GeV)

- ±1 unit range extends beyond R_{ref}, allows margin for manufacturing tolerances
- b2 decreased to 0.5 unit (w.r.t. 3 units in CDR design)

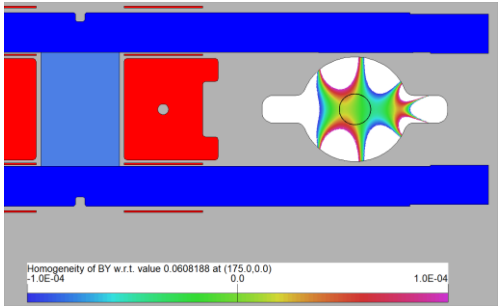


Computed field harmonics

Aperture 84 mm



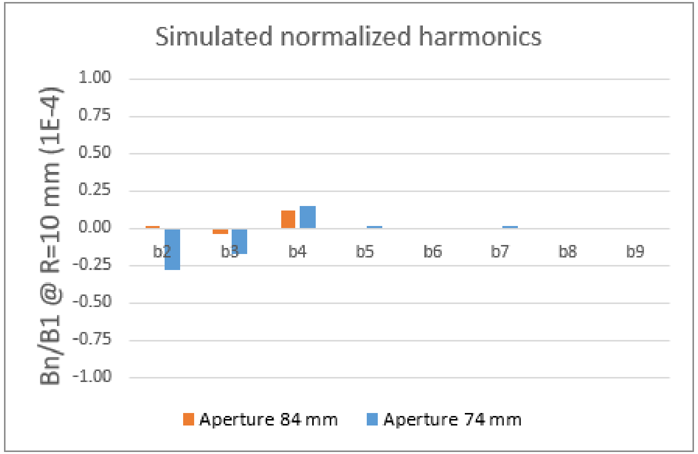
Aperture 74 mm



Dipole field quality

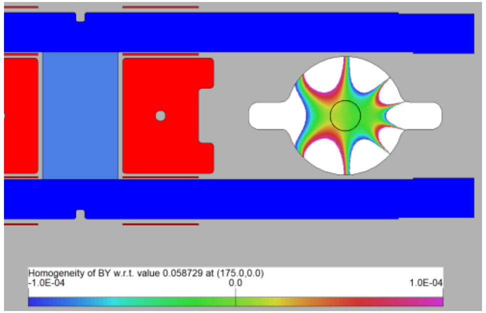
Case 2: peak current, trim coils on (182.5 GeV)

- Trim coils activated to tune B_{peak} by +5% in one aperture and -5% in the other
- Marginal effect from trims on field quality



Computed field harmonics

Aperture 84 mm



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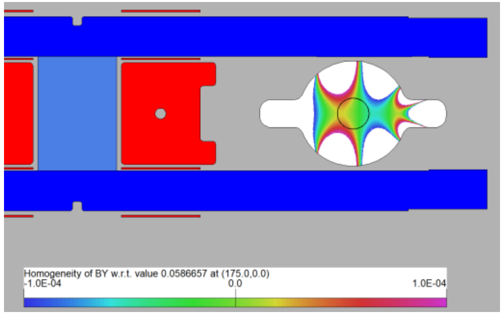
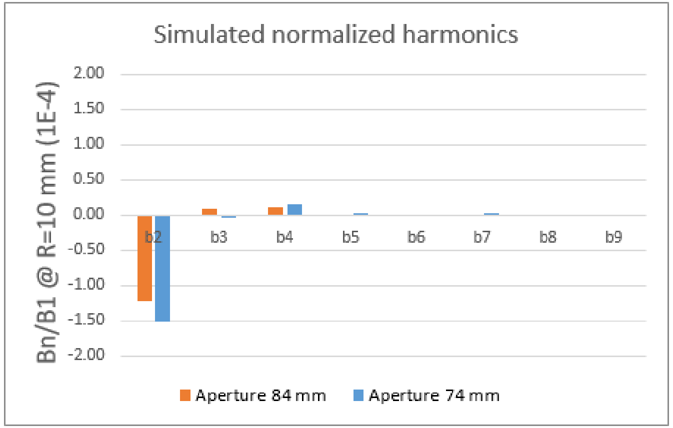


Dipole field quality

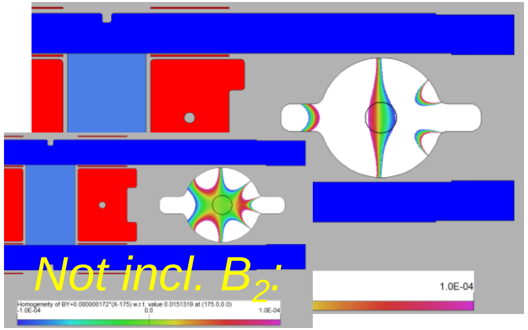
Case 3: 1/4 current, trim coils off (45.6 GeV)

- Slight increase of b_2 at lower field
- Can be compensated with arc quadrupoles
- Will be further evaluated with prototype magnet

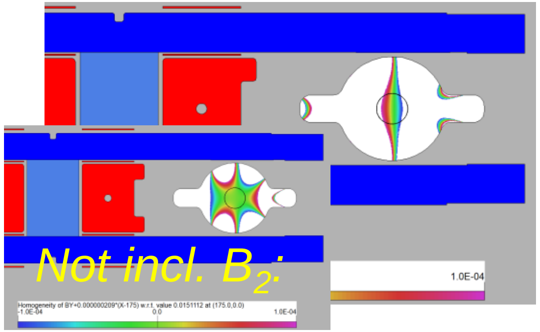


Computed field harmonics

Aperture 84 mm



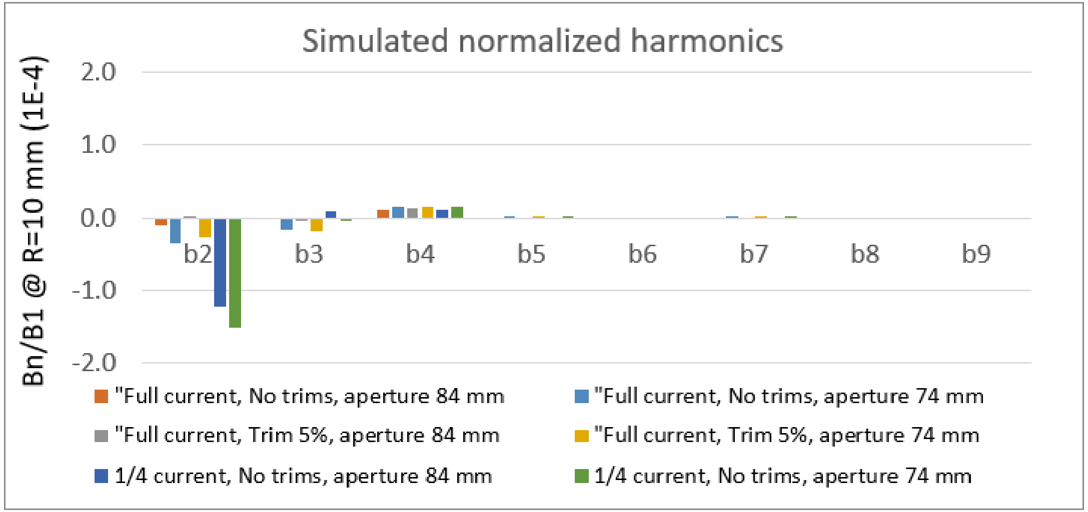
Aperture 74 mm



Dipole summary

- The magnet geometry has been optimized to further limit **b_2 to <1.5 units** and **other harmonics to <0.5 units**

- The **effect of the trim** coils for the field tapering, tuning and H orbit correction on the **field quality** is **negligible**

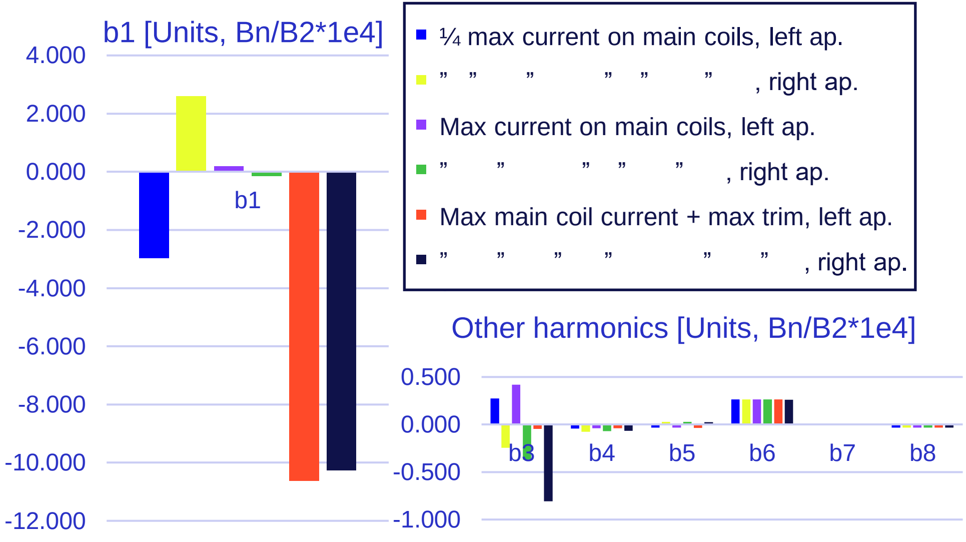


Computed field harmonics

Quadrupole

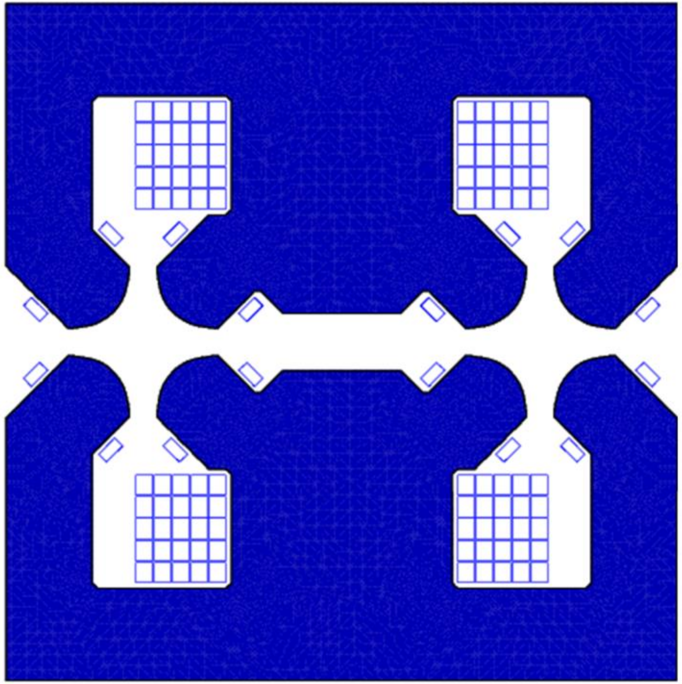
Background – latest collider quad design

- Trim coils at poles, no magnetic gap between apertures.
- Magnetic axis shift much less compared to previous designs (~0.40 mm); worst case b1 is ~10 units, gives ~0.01 mm shift.



Harmonics at reference radius 10 mm, for different powering cases.

Presented at FCC week 2023: "Status of the FCC-ee booster and collider magnet developments", 7th June 2023.



Current collider quad cross section design.
Note the trim coils at the poles of each aperture.

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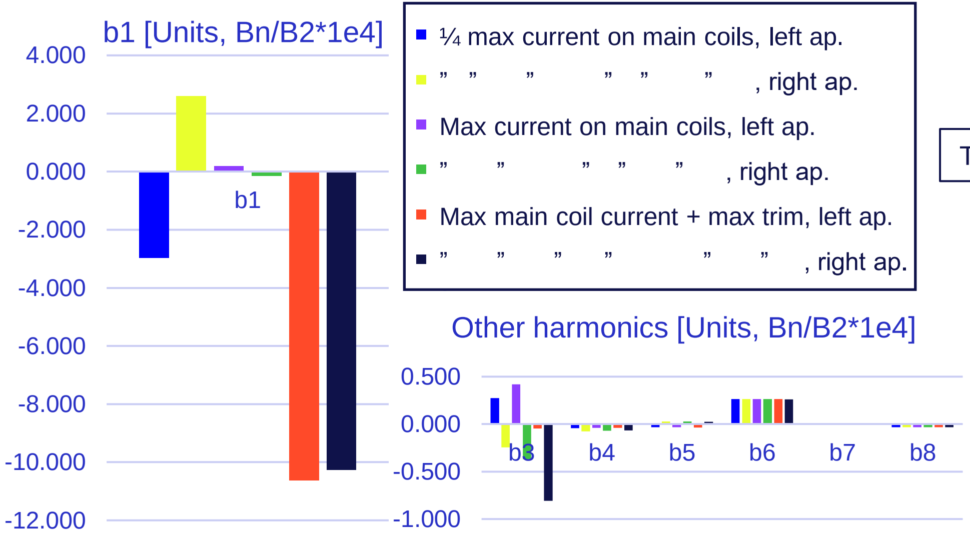

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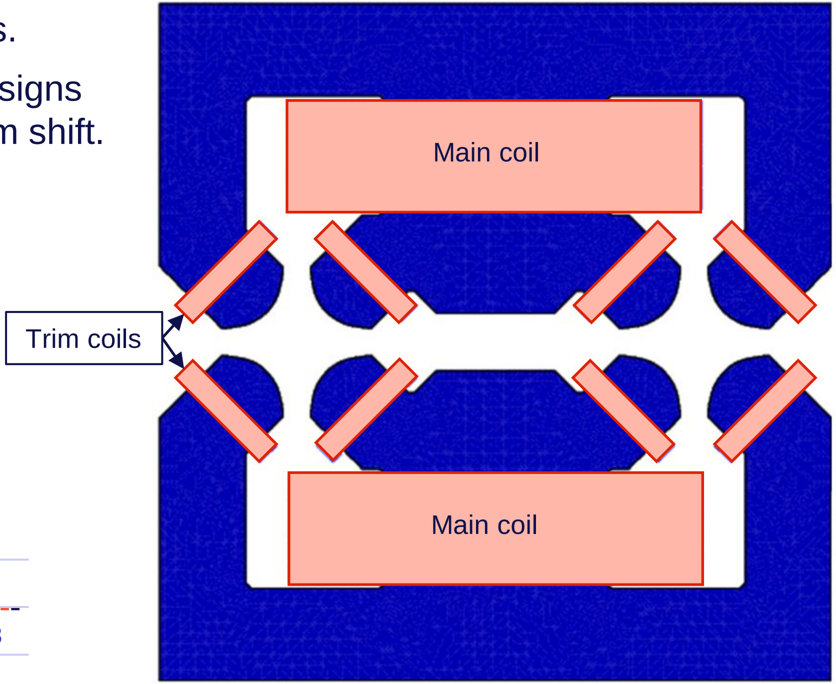
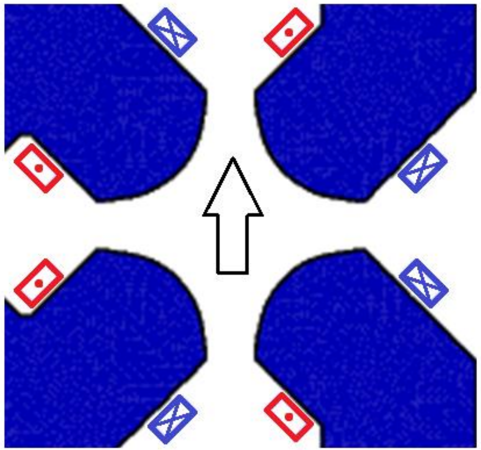


Current collider quad cross section design.
Note the trim coils at the poles of each aperture.

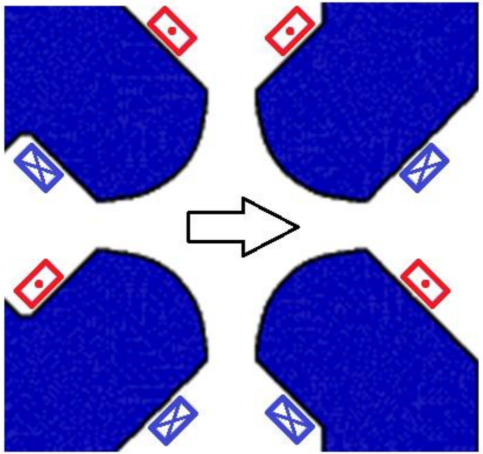
Horizontal & vertical correction

- Previous designs assumed trim coils only used for quadrupolar tapering and tuning.
- Current set-up, with trim coils on poles, could allow for vertical and horizontal correction.
  - Maximum field strength required for correction: $L_{sext} B_{corr,\,sext} = L_{quad} B_{corr,\,quad}$

$$\Rightarrow B_{corr,\,quad} = \frac{1.5\text{ m}}{2.9\text{ m}} 13\text{ mT} = 6.7\text{ mT}$$



Powering setup for horizontal correction (vertical dipole).



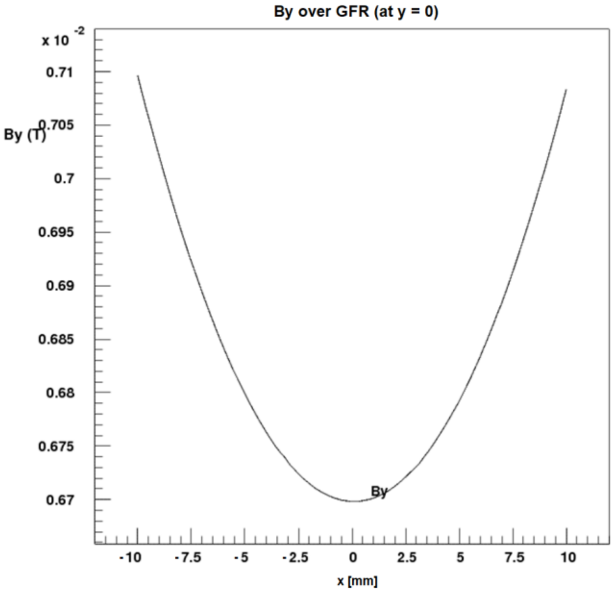
Powering setup for vertical correction (horizontal dipole).

Horizontal correction (quad main coil off): field quality

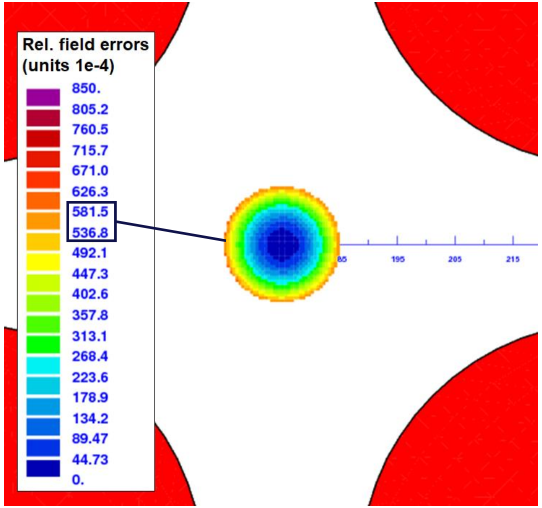
- Field quality dB/B ≈ 6%.
- Large sextupole component introduced:

Rref = 10 mm	Main harmonic: B1
b1	10000.000
b2	-9.499
b3	**578.806**
b4	-0.005
b5	5.581
b6	0.000
b7	-0.292
b8	-0.001
b9	-0.006
b10	0.000

Harmonics of the horizontal correction dipole (vertical field).



Dipole field over GFR.



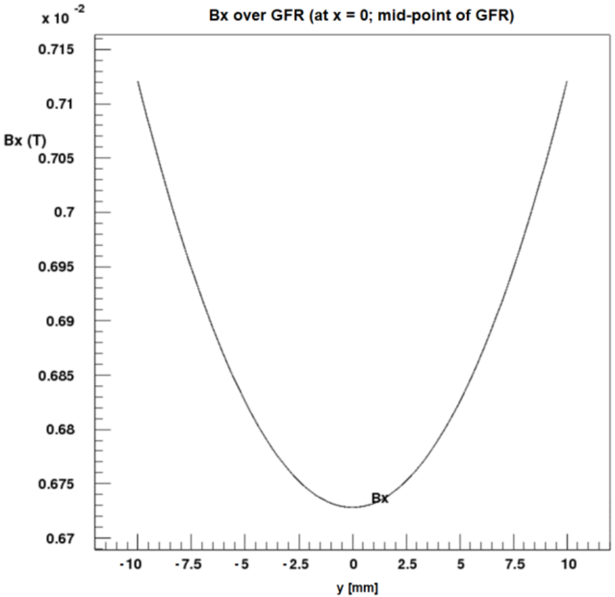
Field quality in GFR.

Vertical correction (quad main coil off): field quality

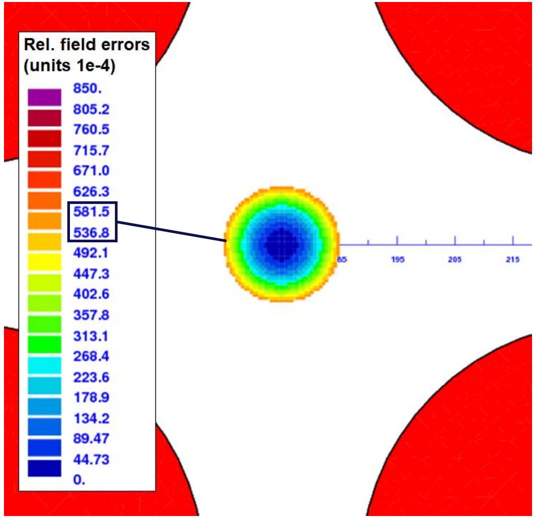
- Same as for horizontal corr., due to pole symmetry, but components are skew.
- Field quality dB/B ≈ 6%.
- Large (skew!) sextupole component introduced:

Rref = 10 mm	Main harmonic: A1
a1	10000.000
a2	0.265
a3	**-577.456**
a4	0.032
a5	5.659
a6	0.002
a7	0.295
a8	0.000
a9	-0.006
a10	0.000

Harmonics of the vertical correction dipole (horizontal field).



Dipole field over GFR.



Field quality in GFR.

Field quality w.r.t. main quad field (main coils on)

- Sextupole component introduced by horizontal or vertical correction is not small with respect to the main quad field.
- The question is: is it acceptable?

Rref = 10 mm	Main harm: B2	Rref = 10 mm	Main harm: B2
b1	554.930	a1	0.000
b2	10000.000	a2	0.000
b3	**31.367**	a3	0.000
b4	0.001	a4	0.000
b5	0.345	a5	0.000
b6	0.271	a6	0.000
b7	-0.018	a7	0.000
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max horizontal correction.

Rref = 10	Main harm: B2	Rref = 10	Main harm: B2
b1	-4.357	a1	554.098
b2	10000.000	a2	0.020
b3	-1.004	**a3**	**-31.996**
b4	0.000	a4	0.002
b5	0.033	a5	0.313
b6	0.271	a6	0.000
b7	-0.002	a7	0.016
b8	-0.005	a8	0.000
b9	0.000	a9	0.000
b10	-0.003	a10	0.000

Harmonics of quadrupole field with max vertical correction.

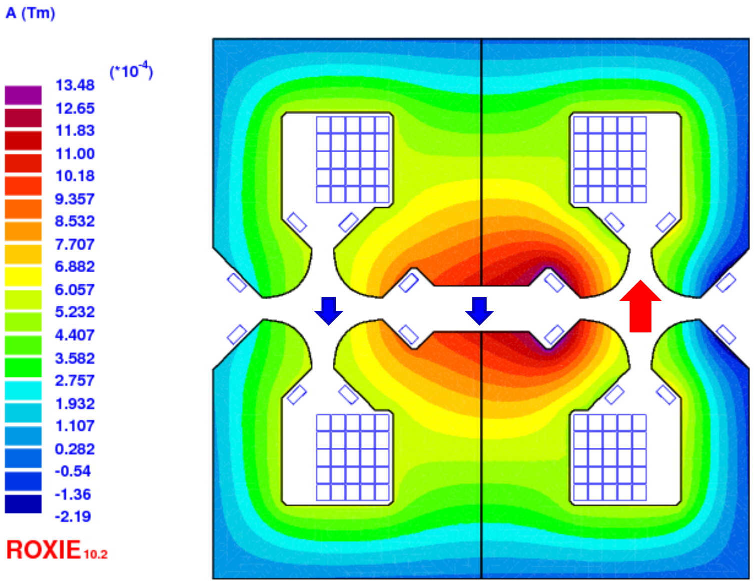
Powering requirements

Horizontal correction:

- Large cross-talk; opposing aperture must apply an opposing correcting field to compensate.
  - Worst case is when B1 = +6.7 mT is required on both apertures; each trim coil needs **NI = 477 A** to compensate cross-talk.

Vertical correction:

- Minimal cross-talk; **NI = 177 A** per trim coil to achieve max corr. field.



Plot showing potential field lines with only right aperture horizontal correction powered, and no compensation on the left aperture trim coils. Flux leaks into the left aperture.

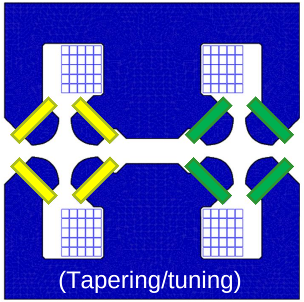
Circuit requirements

1. If only quadrupolar tapering / tuning is needed, all trim coils in each aperture can be powered in series
   → **1 trim coil power supply <u>per aperture</u>.**

2. If either vertical or horizontal correction is required, each pair of adjacent trim coils can be powered in series
   → **2 trim coil power supplies coils <u>per aperture</u>**.

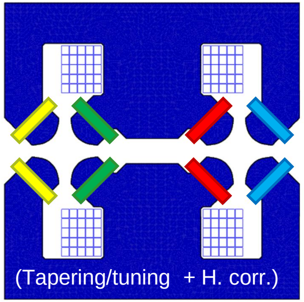
3. If both vertical and horizontal correction is required, each trim coil needs to be powered independently
   → **4 trim coil power supplies <u>per aperture</u>.**

1.

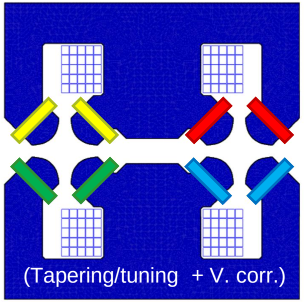


<u>Powered by:</u>
- power supply # 1
- “ “ # 2
- “ “ # 3
- “ “ # 4
Etc…

2.



or



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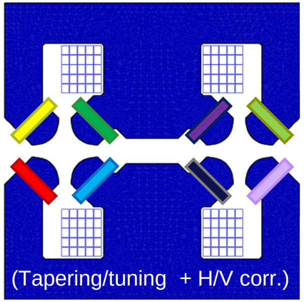


Conclusions for quadrupole

- Large sextupole component introduced in both horizontal and vertical correction.

  → In the vertical correction case, this means a skew sextupole.

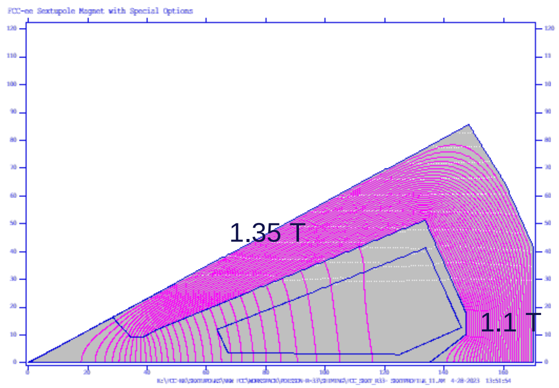
- Horizontal correction would require extra power to compensate for cross-talk in opposing aperture.

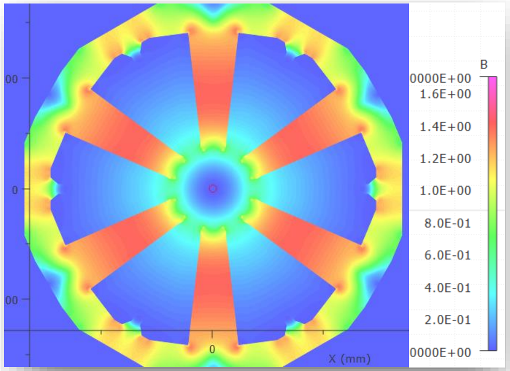
  → probably not a viable solution.

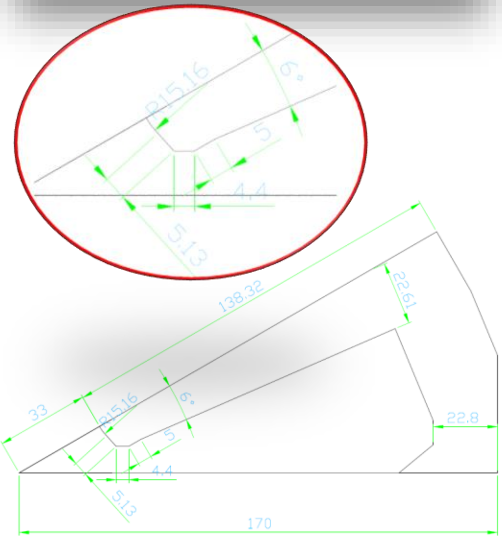
Sextupole

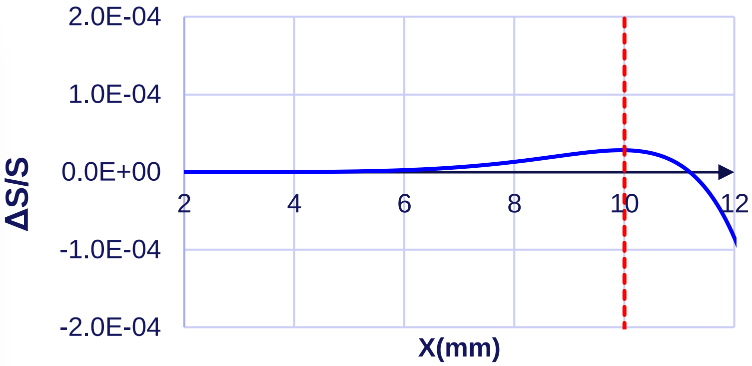
Main Sextupole

Parameter	Unit	Updated June 2023
Inter-beam distance	mm	350
Sextupole strength	T/m2	880
Aperture radius	mm	33
Magnetic length	m	1.5
Pole tip field	T	0.48
Good field region	mm	±10
Field quality in GFR	-	1.0E-04

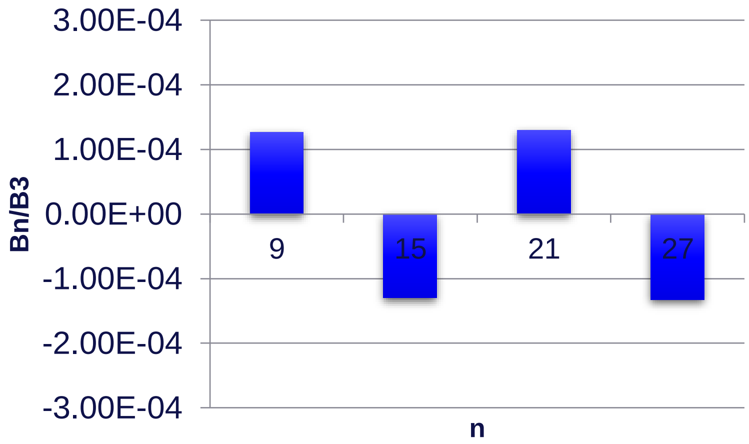






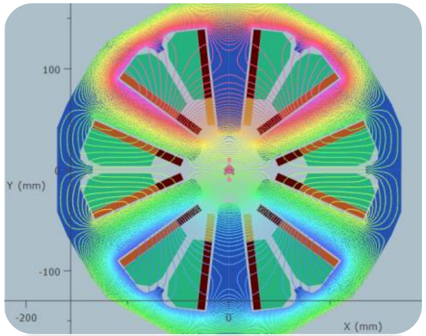


➤ Field quality better than 1E-04

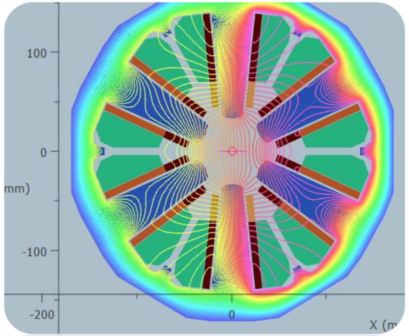


Auxiliary Coils as Correctors

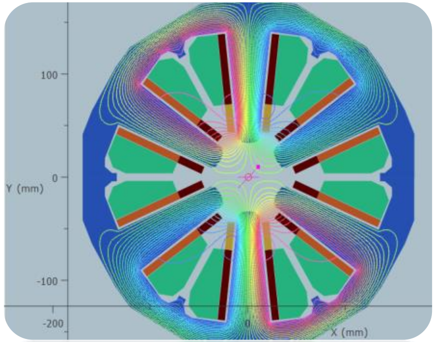
Vertical Corrector



Horizontal Corrector

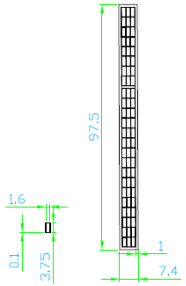


Skew Quadrupole Corrector

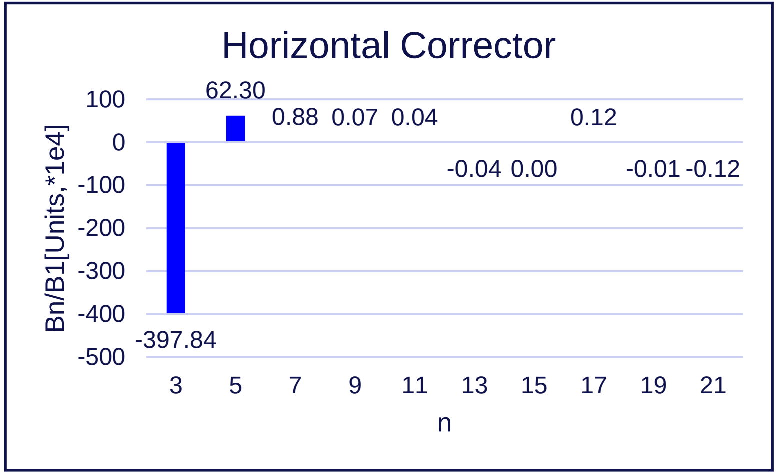


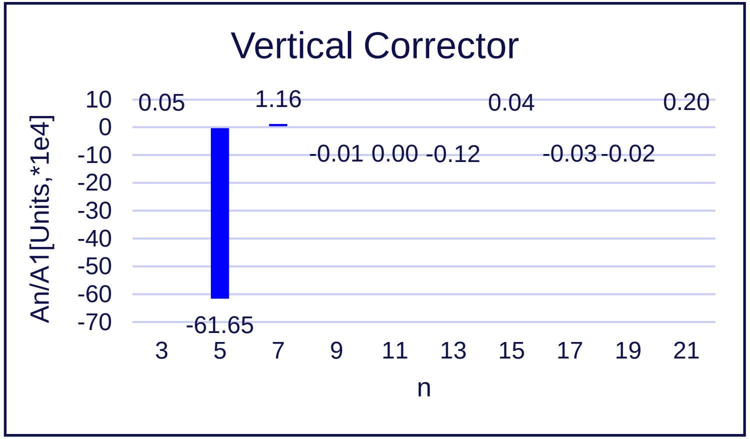
Green Coils: Main Sextupole
Orange Coils: Vertical Corrector
Brown Coils: Horizontal Corrector
Yellow Coils: Skew Quadrupole

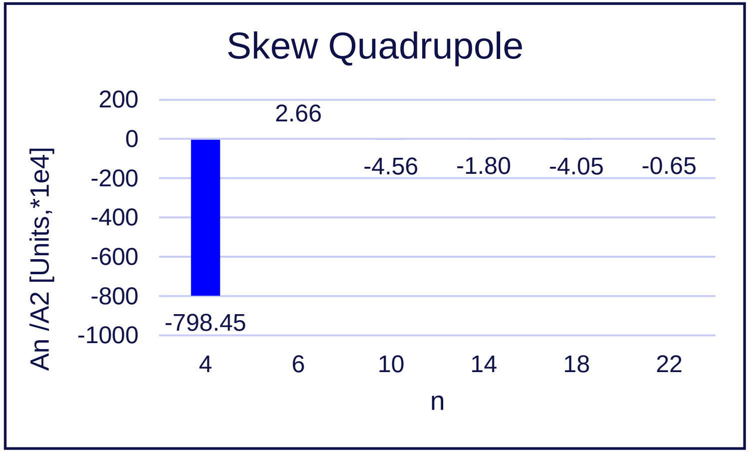
Parameter	Ver. Corrector	Horiz. Corrector	Sk. Quad. Corrector
Integrated Strength(Tm)(T)	0.02	0.02	0.6
Magnetic field (mT)/(T/m)	13	13	0.4
Effective length (mm)	1500	1500	1500
Ampere-Turns per pole (A.t)	345	400/200	378
Number of turns	48	48-24	24
Conductor size (mm^2)	3.75 × 1.6	3.75 × 1.6	3.75 × 1.6
Current (A)	7.2	8.3	15.8
Current Density (A/mm^2)	1.2	1.4	2.6
Resistance per magnet (Ω)	1.7	1.7/0.8	1.3
Total Voltage (V)	12.1	14/7	20
Total Power (W)	87	118/59	315



Individual Correctors (main sextupole coils off)



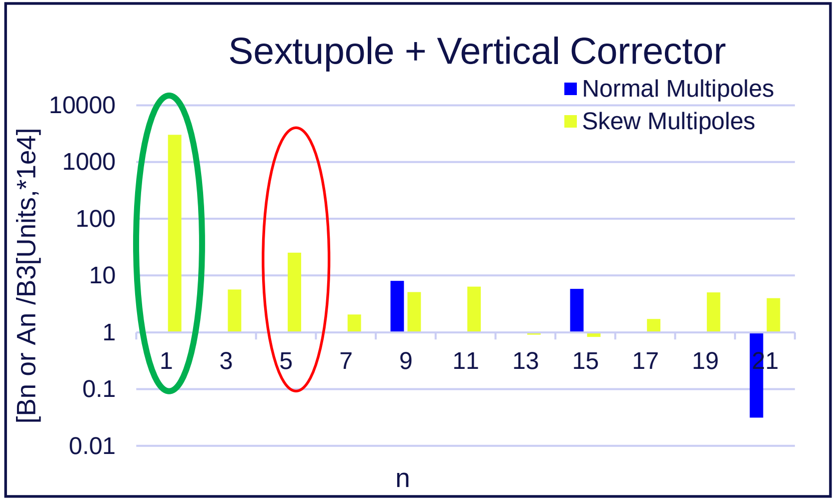


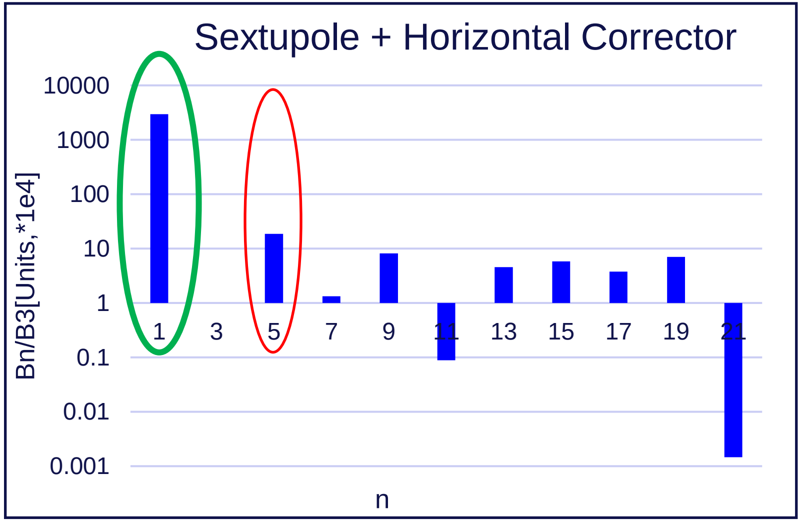


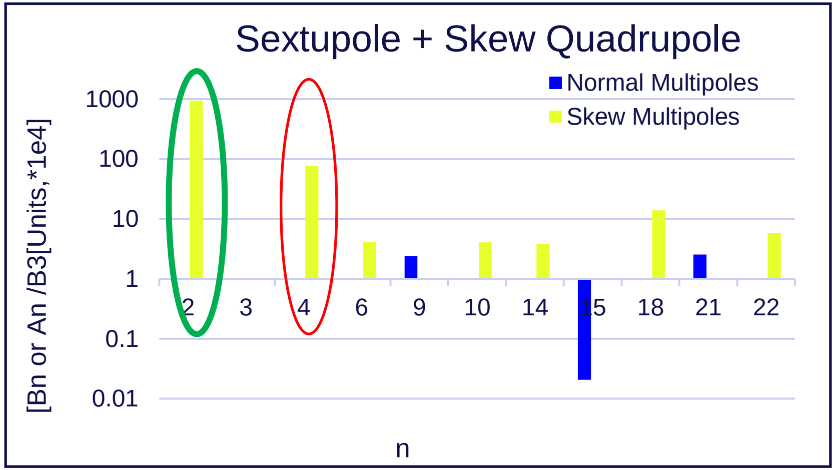
- The Horizontal dipole corrector brings in a **strong normal sextupole** component that can be cured by the main sextupole coil.
- The Horizontal/Vertical dipole correctors bring **strong normal/ skew decapole** components.
- The Skew Quadrupole corrector introduces a **strong skew octupole** term. (**<u>800 Units! </u>**not allowed multipole but there is, since it is not a pure skew quadrupole magnet!

Field Quality
Contribution of each corrector

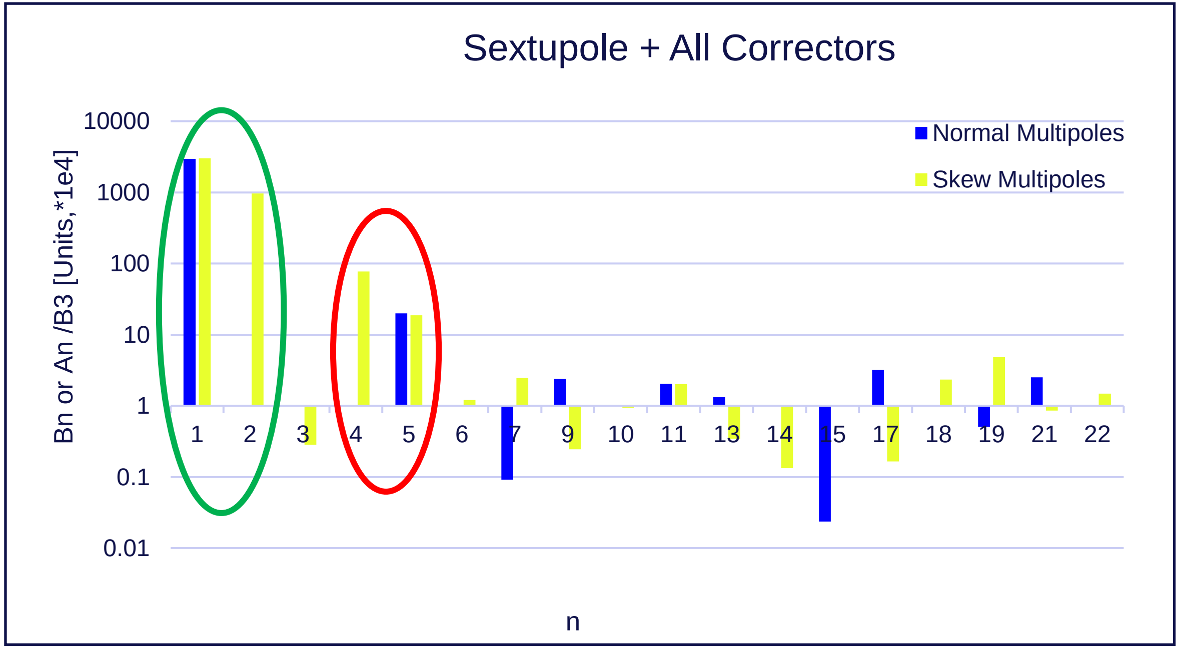
✓ The main circuit and only one of the trim circuits are powered…

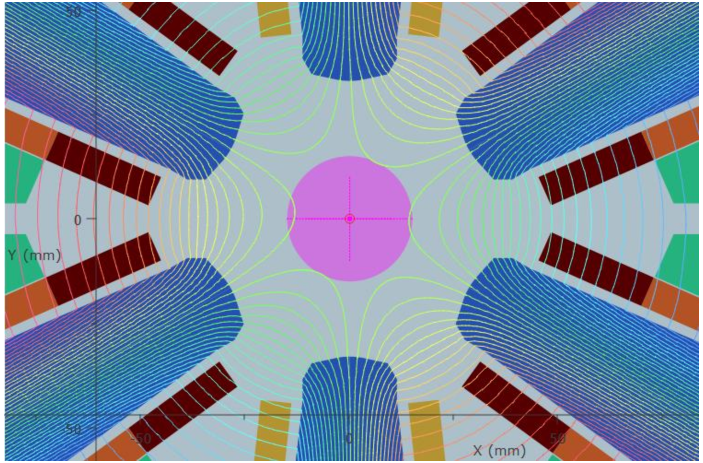






Field Quality
Sextupole with all correctors ON





Conclusions for sextupole

- The Horizontal and Vertical dipole corrector brings **strong decapole** components.
- The Skew Quadrupole corrector introduces a **strong skew octupole** term.
- Higher order multipoles (specially n=4, n=5) should be investigated to finalize the configuration of correctors in the lattice.
- In all cases these perturbations are more modest if **a smaller region** around the magnetic centre is considered (smaller GFR).

Conclusions

Conclusions

The **field quality** of the **orbit correction** and **skew quadrupole** circuits generated by trim coils in the **sextupoles** has been evaluated.

- Up to **~25 units of normal/skew decapoles** are expected from orbit correction;
- Up to **~75 units of skew octupole** are expected from the skew quadrupole.

Options have been explored to **host the orbit correction circuits in the dipoles and quadrupoles**, using the field tapering trim coils.

- This could make more room for the sextupole main coil and **reduce its power consumption**.
- It offers **orbit correction granularity** at **every arc half-cell**.
- The operation with a **fast feedback system** needs to be **verified** (solid iron yokes).

The **H orbit correction** could be made by the **dipole trim coils**, with no impact on the field quality.

The **V orbit correction** could be made by the **quadrupole trim coils**, though generating up to **~30 units of skew sextupole**.

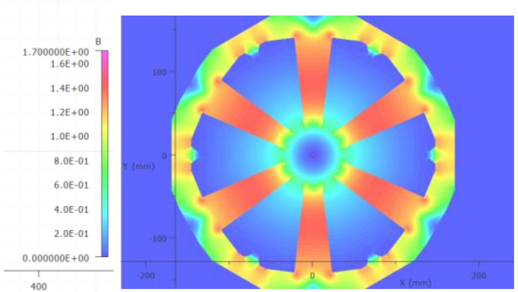
FCC

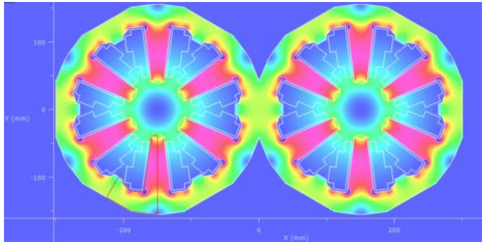
Thank you for your attention!

Questions?

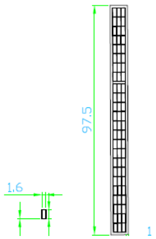
SPARE SLIDES

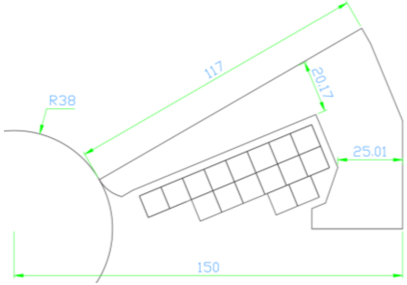
Comparing the Collider Sextupole Electrical and Cooling Parameters

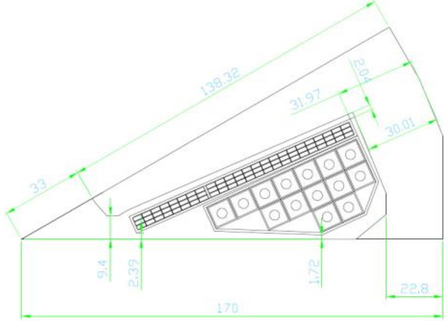




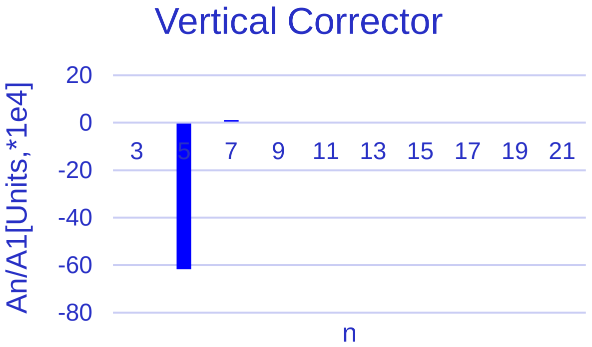
Parameter	Unit	CDR (2019)	New (June 2023)
Inter-beam distance	mm	300	350
Sextupole strength	T/m2	807	880
Aperture radius	mm	38	33
Magnetic length	m	1.4	1.5
Pole tip field	T	0.59	0.48
Total current	At	6300	4250
Number of turns per coil	-	14	14
Operation current	A	448	304
Conductor dimensions	mm^2	8×8	8.5×8.5
Cooling diameter	mm	3	4
Current density	A/mm^2	7.87	5.1
Voltage drop per magnet	V	34.3	23.4
Resistance per magnet	mΩ	76	79
Power per magnet	kW	15.4	7.3
Number of water circuits	-	18	6
Water temperature rise	°C	10.4	13.4
Cooling water speed	m/s	2.77	1.75
Pressure drop	bar	6	6
Reynolds no.	-	4160	3450
Conductor length/magnet	m	255	277
Conductor mass/magnet	kg	128	147
Trim coil dimensions	mm	-	3.75 × 1.6
Number of trim coils	-	-	48+24
Trim coil length/magnet	m	-	1327

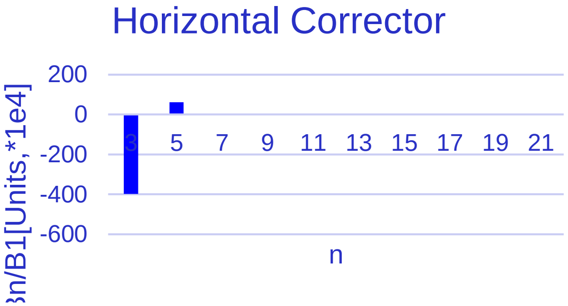


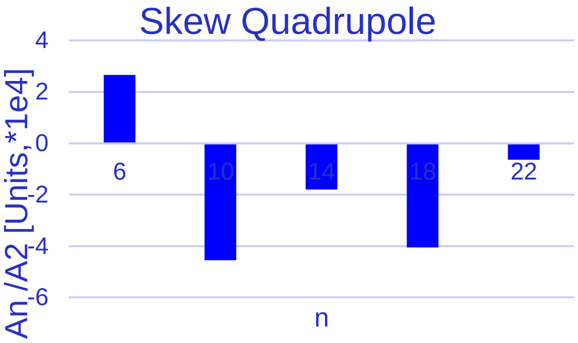


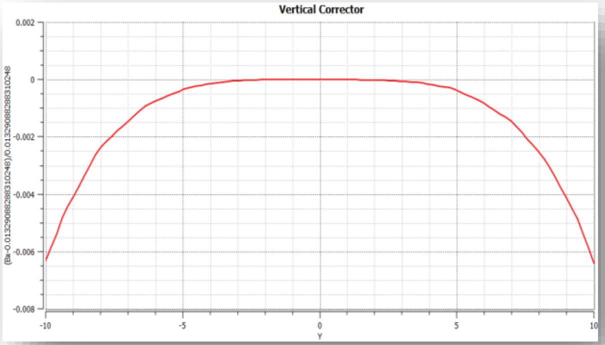


Individual Correctors (main sextupole coils off)



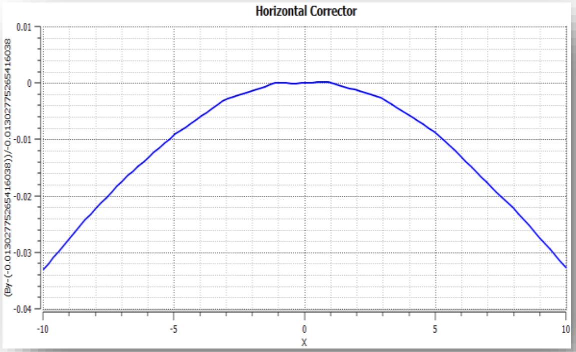






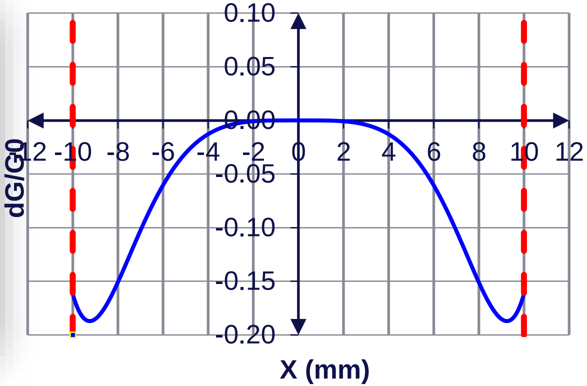
Bx field homogeneity

Bx(0) = 0.013 T



By field homogeneity

By(0) = 0.013 T



Gradient homogeneity

G(0) = 0.4 T/m

Field quality of sextupole plus correctors

$$B = B_{SEXT} + B_{VD} + B_{HD} + B_{SQ} \,.$$

Considering the sextupole and the vertical dipole corrector $\zeta = (x + iy)$

$$B_{SEXT} = \frac{B_{3,SEXT}}{10000}\left[10000\left(\frac{\zeta}{R}\right)^2 + b_{9,SEXT}\left(\frac{\zeta}{R}\right)^8 + b_{15,SEXT}\left(\frac{\zeta}{R}\right)^{14} + \ldots\right],$$

$$B_{VD} = \frac{B_{1,VD}}{10000}\left[10000 + b_{3,VD}\left(\frac{\zeta}{R}\right)^2 + b_{5,VD}\left(\frac{\zeta}{R}\right)^4 + b_{7,VD}\left(\frac{\zeta}{R}\right)^6 + b_{9,VD}\left(\frac{\zeta}{R}\right)^8 + \ldots\right],$$

Combining the two expressions and normalizing by the sextupole fundamental component yields:

$$B_{SEXT} + B_{VD} = \frac{B_{3,SEXT}}{10000}\left[10000\left(\frac{\zeta}{R}\right)^2 + b_{9,SEXT}\left(\frac{\zeta}{R}\right)^8 + b_{15,SEXT}\left(\frac{\zeta}{R}\right)^{14} + \ldots\right.$$
$$\left. + \frac{B_{1,VD}}{B_{3,SEXT}}10000 + \frac{B_{1,VD}}{B_{3,SEXT}}b_{3,VD}\left(\frac{\zeta}{R}\right)^2 + \frac{B_{1,VD}}{B_{3,SEXT}}b_{5,VD}\left(\frac{\zeta}{R}\right)^4 + \frac{B_{1,VD}}{B_{3,SEXT}}b_{7,VD}\left(\frac{\zeta}{R}\right)^6 + \ldots\right].$$

The contribution to the multipoles coming from the correctors is **directly proportional to the corrector strength** and **inversely proportional to the main sextupole field**,

$$\boxed{b_5 = \frac{B_{1,VD}}{B_{3,SEXT}}b_{5,VD} \;,\quad b_7 = \frac{B_{1,VD}}{B_{3,SEXT}}b_{7,VD} \;,\quad b_9 = b_{9,SEXT} + \frac{B_{1,VD}}{B_{3,SEXT}}b_{9,VD} \;,\quad \ldots}$$

From: A. Milanese

Field quality (sextupole plus correctors)

$$By(x.y=0) = \left(B_H + S\frac{x^2}{2}\right) + b_5x^4 + b_7x^6 + b_9\,x^8 + \ldots$$

$$Bx(x.y=0) = (B_V + g_x x) + b_3x^2 + b_5x^4 + b_6x^5 + b_7x^6 + b_9\,x^8 + b_{10}\,x^9 + \ldots$$

$$\frac{\Delta By}{By_0}(x) = \frac{B_y - (B_H + S\frac{x^2}{2})}{B_H + S\frac{x^2}{2}} = \frac{b_5x^4 + b_7x^6 + b_9\,x^8 + \ldots}{B_H + S\frac{x^2}{2}}$$

$$\frac{\Delta Bx}{Bx_0}(x) = \frac{B_x - (B_V + g_x x)}{B_V + g_x x} = \frac{b_3x^2 + b_5x^4 + b_6x^5 + \cdots}{B_v + g_x x}$$

57 mT

17 mT